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Functional Specification

ON THE MEASUREMENT OF THE TUNES, COUPLING & DETUNINGS WITH MOMENTUM AND AMPLITUDE IN LHC

Abstract

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History of Changes

Rev. No.	*Date*	*Pages*	*Description of Changes*
	2/10/2002		Create the first skeleton of the document
	27/11/2002		Sections on Ranges and Tolerances
			+ scenarios,…damper parameters,…

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1. SCOPE

This functional specification defines the requirements for the measurement of the betatron tunes, the betatron coupling, and their variations with momentum or oscillation amplitudes. The transverse beam excitation devices are included. The passive measurement methods based on the Schottky noise will be dealt with in a separate document. This document completes the Conceptual Design Report [1].

2. DIRECT OBSERVABLES AND DERIVED BEAM PARAMETERS

All methods considered in this document require the beam to be subject to coherent transverse oscillations. These can be either due to a kick or to a sustained sinusoidal or band pass excitation. The primary observable is the time sequence of the turn-by-turn beam positions observed at one machine azimuth. For most methods, the position of the beam center of gravity matters. For one method [2], the positions of the head and of the tails are necessary.

The variation [Eq. 1] of the betatron tune with momentum and oscillation amplitude allows the calculation of the linear and relevant higher-order chromaticities Q', Q'', Q''', of the anharmonicities Q'_J and the chromo-geometric detunings $Q''_{J\delta}$.

$$\Delta Q = Q_0 + \frac{\partial Q}{\partial \delta}\delta + \frac{1}{2}\frac{\partial^2 Q}{\partial \delta^2}\delta^2 + \frac{1}{6}\frac{\partial^3 Q}{\partial \delta^3}\delta^3 + \ldots + \frac{\partial Q}{\partial J} J + \ldots + \frac{\partial^2 Q}{\partial J\, \partial \delta} J\,\delta + \ldots$$

$$\Delta Q = Q_0 + Q'\delta + \frac{1}{2}Q''\delta^2 + \frac{1}{6}Q'''\delta^3 + \ldots + Q'_J\, J + \ldots + Q''_{J\delta}\, J\,\delta + \ldots \qquad \text{Eq. 1}$$

$$with \quad \delta = \frac{\Delta p}{p}, \quad x = \sqrt{\beta}\sqrt{2J}\,\sin(\mu)$$

The variation of the coupled tunes with focusing provides the modulus of the coupling vector. Other methods under development aim at observing directly the linear chromaticity [2][3], the coupling vector $|\vec{c}|$ and the local coupling coefficients [4].

As will be shown in the following, the measurement of these more involved beam parameters are important in LHC to compensate the non-linearity induced by the persistent currents of the super-conducting dipoles using the non-linear correctors.

3. BEAM AND MACHINE CONDITIONS

The measurement of the tunes is a basic requirement to operate the machine. It shall thus be robust, i.e. usable in a wide range of beam and machine conditions. This includes pathological cases where the damping of the coherent oscillations takes place over a small number of turns to physics conditions where the amplitude of any coherent oscillation must be small enough to remain compatible with the collimation scheme.

3.1 RANGE OF BEAM CURRENTS, BUNCH SPACINGS AND BUNCH LENGTHS

The ranges of the LHC beam parameters shown in Table 1 are based on the v6.4 parameter list [5] and extended as follows:

- the lowest proton and Pb intensity to be detected corresponds to the sensitivity threshold of the BPM's.

- the range of bunch length covers a possible bunch lengthening in the SPS for injection studies with a narrow momentum spread (G. Arduini).

Table 1: Range of LHC beam currents and related parameters (the nominal values are underlined)

Particle	*Bunch charge*	*Number of bunches*	*Bunch spacing*	*RMS Bunch length*
	q		*ns*	*ns*
proton	$2\ 10^{9} \rightarrow$ $\underline{1.15\ 10^{11}} \rightarrow$ $1.7\ 10^{11}$	1 → 2808	24.95 -> 88925	.28 -> .62
Pb	$2\ 10^{9} \rightarrow$ $\underline{5.6\ 10^{9}} \rightarrow$ $8.2\ 10^{9}$	60 → 592	100→1350	

The initial bunch spacing will be 75 ns rather than 25 ns at the commissioning time, as long as the beam scrubbing is necessary. In a beam, not all bunches are separated by the same amount due to the injection and abort gaps. The exact nominal beam structure may be consulted in [6].

3.2 SCENARIOS OF OPERATION

The various measurement methods discussed in this specification all involve the observation over a given time of a dipole moment. Hence the ingredients which define the scenarios of operation are:

- The beam current range,
- The amplitude range for the transverse oscillation
- The coherence length of the oscillation, depending on the beam tune spread and active transverse feedback applied.

3.2.1 BEAM CURRENT RANGE

It is presented in Table 1. It should be noted that the pilot beam intensity corresponds to several uses with different requirements.

- At the beginning of a regular fill: the requirements are then relaxed and can be identical as the commissioning case. The fine machine tuning can be done with a higher intensity
- Many studies, especially at 7 TeV, will require the use of a single pilot bunch to minimize the probability of quenching a magnet. In this case the nominal precision is expected.
- The intensity of the Pb ions for physics is identical to that of a pilot bunch; the nominal precision is expected as well.

The scenarios are under study by Oliver. A first draft came on 3/12/03. Probably a few iterations are needed before this section is rewritten.

3.2.2 COMMISSIONING AND MACHINE SET-UP WITH PILOT BEAMS

The operation with pilot bunches is necessary for the machine commissioning and possibly as a first step in each run if the machine reproducibility is not sufficient to prevent quenches. In this mode of operation, we can assume that all space-charge and beam-beam phenomena are negligible. The damper will only be used for the first turns to damp out the injection oscillations and will otherwise be switched off. The Landau damping octupoles will ~~not~~ only be turned on at top energy. The betatron coupling can be large (section 4.2) and the decoherence may occur within a small number of turns at injection energy (section 9).

Some of the important goals of this operation stage will be:

- measurement of the tunes, chromaticity and coupling (?? Are the feed-dwns large??) changes during the injection, snap-back and ramp, (Yes the feed-down can be large (a2=0.2 units for MCS systematically misaligned by 0.3 mm and <b3>=-6 units expected at injection for Xs3 magnets. a2=0.2 => c_-=0.03
- measurement of the b_5 imperfection and correction accuracy via a measurement of Q‴.
- possibly measurement of the amplitude detunings.

It should be noted that these measurements require a large number of kicks to the beam and will possibly involve emittance blow-up issues.

3.2.3 NOMINAL OPERATION WITH PROTONS

What about the intensity level? Clarify the use of the damper? Distinguish injection DAMPING and transverse feedback.

In this nominal mode of operation, the bunch intensity is significantly higher. Its range is given in table xx as well as the range for the number of bunches in each beam. As soon as the intensity per bunch/per beam?? Reaches xxx, the damper will be used throughout the run to stabilize the dipole mode of the transverse coherent instability. In the vicinity of the nominal intensity, the Laudau damping octupoles will be switched on during the ramp and the physics data taking to stabilize higher-order transverse modes.

Section 6 summarizes the change of parameters during some critical periods of the run that need to be tracked and corrected. For that purpose, a continuous feedback on the tunes is probably mandatory to reach high performance. In second line, a continuous chromaticity feedback (during injection, snap-back, ramping and squeeze) is likely to both improve the reliability of the tune feedback and prevent loss of particles on resonances or due to collective motion in case of large chromaticity. In third line, a feedback on the betatron coupling would as well improve the reliability of the tune feedback.

The long-range and head-on beam-beam effects may further alter the transverse spectra (to be studied), requiring some sophistication in the analysis of the transverse spectra.

The target for the precision (section zz) is tighter.

The presence of the collimators at all stages of operation, and more specifically at top energy, constrains the maximum oscillation amplitude (section 7)

In most instances, the transverse parameters of the whole beams are the relevant parameters for machine operation and tuning. Their spread over the bunches is more relevant to machine studies and not so much at this stage.

3.2.4 OPERATION WITH 'FIRST YEAR' BEAMS

In at least the first year of operations, the maximum bunch charge shall be limited to 0.4 10^{11}

3.2.5 NOMINAL OPERATION WITH IONS

3.2.6 MACHINE STUDIES

3.2.7 MACHINE OPERATION WITH PHYSICS BEAMS

Intermediate intensities to be included.

What about the intensity level? Clarify the use of the damper? Distinguish injection DAMPING and transverse feedback.

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3.2.8 MACHINE OPERATION WITH IONS

The bunch intensity is as low as that of the pilot proton beam but the number of bunches should improve the transverse signals in a significant way (**Error! Reference source not found.**). *The damper and landau damping octupoles are not foreseen to be used further than injection damping??* The targets for precision are intermediate between s1 and s2.

3.2.9 MACHINE STUDIES

To simplify the dynamics, it may be anticipated that many studies will be carried out with a single, possibly high-intensity, bunch, except beam-beam studies of course.

In this situation, the measurement of the tunes will frequently be used not for itself, but to get access to more involved or more difficult to measure beam parameters. An example is the b_5 in the arcs or the multipoles in the triplets.

The requirements on accuracy are therefore much tighter (section…) but one can assume that the machine is well tuned to favour this kind of measurement.

The bunch-by-bunch measurement of the tunes can be used to identify and cross-check the presence of an electron cloud or of the PACMAN effect. These effects being subtle, it is necessary to detect several of their consequences to identify them in a finite time.

The study of the non-linearity involves large amplitude oscillations, as much as is allowed by the geometrical aperture. To prevent quenches, it is likely that pilot pulses have to be used.

4. EXPECTED RANGE OF THE OBSERVABLES / PARAMETERS

The analysis of the expected ranges of the beam parameters is done to specify the corresponding dynamic range of the instruments.

4.1 TUNE

The nominal LHC tunes were chosen close to the third-order resonances based on Sp$\bar{p}$S [7] and Tevatron experience. The injection and collision tunes are 64.28/59.31 and 64.31/59.32. Alternative working points are anticipated, such as $Q_{x,y}$=.232/.242, $Q_{x,y}$=.385/.395 or $Q_{x,y}$=.405/.410 [7]. The tunes shall be kept constant over a full machine cycle except for the small shift between injection and collision nominal tunes. The best performance in the ISR was achieved with the tip of the tune footprint at .9955. This may be impossible in the LHC due to the amplification of the linear imperfections. It shall however not be excluded a priori.

4.2 COUPLING

The dominant coupling source arises at injection from the a_2 uncertainty of the main dipoles and in collision from the random roll angle errors of the inner triplet quadrupoles. For LHC, the difference coupling resonance, characterized by $|c_-|$ dominates the beam dynamics. For accurate coupling compensation in collision ($|c_-|$ less than a few 10^{-3}), the sum resonance coefficient c_+ shall as well be taken into account.

The maximum coupling at injection was estimated in [8]. After revaluation using the latest magnetic measurements, the systematic and random components (r.m.s.) of the coupling are: $c_- = 0.109 \pm 0.03$ and $c_+ = 0.006 \pm 0.03$. The systematic part assumes a_{2u}(dipoles)=0.5 units, a maximum systematic misalignment of the b_3 spools pieces by +/- 0.3 mm for a correction of b_3 = −6 units and additivity of the arc contributions. The random part assumes a_2(dipoles)=1.9 units rms, an rms misalignment by 0.5 mm of the spool pieces, a vertical rms orbit of 2 mm and a rms roll of the quadrupoles by 0.5 mrad. This worst case corresponds to the first line in Table 2. The accuracy of latest strategy for magnetic measurements [9] should allow a gain by about a factor of two before beam measurements. Nevertheless, the machine at injection may be initially fully coupled. A larger tune split will be necessary, e.g. .285/.385 [8].

Table 2: Maximum coupling expected

	Energy	$\|c_-\|$	$\|c_+\|$
Worst case (2σ)	450 GeV	.17	.07
After correction based on magnetic measurements	450 GeV	.10	.07
MQX roll within tolerance	7 TeV	.05	.12

In collision the residual roll of the insertion quadrupoles can potentially produce a very large coupling. This effect however shall be reproducible from run to run and can be studied by a progressive squeeze. We therefore only consider the coupling contribution for an alignment within tolerance: $c_- \sim c_+ < 0.05$ before correction for two insertions squeezed to $\beta^* = 0.5$m and an rms alignment to 0.2 mrad [10].

4.3 LINEAR CHROMATICITY

The nominal chromaticity of the LHC is chosen to be $Q'_{x,y}$ =2 units in both transverse planes. It is kept slightly positive to prevent a head-tail instability at nominal current and not too large to avoid particles being pushed onto dangerous resonances during the synchrotron oscillation.

During the commissioning phase of the LHC, it might be difficult to initially control the chromaticity to better than about 10% of its natural value. This corresponds to a chromaticity range of ± 50 units.

For nominal operation, the run-to-run reproducibility of the machine is limited by the precision of the LHC Magnetic Reference System used for machine set-up. According to the cold magnetic measurement of the first 50 main dipoles the reproducibility error amounts to 0.5 units r.m.s. at injection. After anticipation based on 8 reference magnets, the average residual b_3 should not exceed $2 \times 0.5 / \sqrt{8} = 0.35$ units at confidence level of 95%. This corresponds to a linear chromaticity range of around ± 15 units.

4.4 SECOND ORDER CHROMATICITY

In the LHC, the second order chromaticity may become large enough to require monitoring and correction when possible. The main contributions arise either from geometric field imperfections in the main dipoles (the ring integral of b_4, proper azimuthal harmonics of a_3), from some correction systems (Landau octupoles, b_4 spool pieces) or from the chromatic aberration of the low-β insertions.

- The uncertainty of b_4 , b_{4U} =0.4 units [11, Tab. 15] leads to a statistical ring integral $< b_4 >= 0.5^* \, b_{4U} = 0.2$ units [11, p.49]. Its contribution to Q'' is given by [11, Tab. 22]:

$$|Q''| \approx 12000 \times < b_4 > \approx 2500$$

- For its expected value a_{3U}=0.87 (Error table 9901), the contribution of the uncertainty on a_3 may lead in the worst case (additive phases amongst arcs) to [11, p37]:

$$|Q''| \approx 33000 \times a_3^2 \approx 25000$$

for a tune split of 0.01 (collision) and three times less at injection where the tune split reaches 0.03. This contribution can be corrected using the skew sextupole correction scheme. The magnetic measurement of the dipoles so far seems to indicate that the uncertainty on a_3 could be 3 times smaller than anticipated.

- The Landau octupole scheme [12] is devised to produce at 7 TeV an amplitude detuning of about ΔQ ($1\sigma_{ms}$)=0.12 10^{-3} [jp]. Being located in the LHC arcs, they also induce a second order chromaticity of the order of Q''_x=24'000 and Q''_y=10'000, when the scheme is fully excited at 7 TeV [11, Tab. 22].
- According to [13], when two IR's are squeezed to β^*=0.5, the second order chromaticity induced by the low β-quadrupoles can vary from -8'000 to 19'000 depending on the phase advances from IP to IP. This contribution can be corrected by a proper use of the four sextupole correction circuits.

4.5 THIRD ORDER CHROMATICITY

At injection, the main source of third order chromaticity comes from the systematic decapole field imperfections of the main dipoles. It is given by the following scaling law [11, Tab. 23] in the absence of b_5 correction:

$$Q'''_x = 4.9\ 10^6 \times b_{5S} \qquad Q'''_y = -3.1\ 10^6 \times b_{5S}$$

The systematic b_5 is expected to meet the tolerance of 1.1 units maximum at injection [11, Tab. 15]. A reduction of the third order chromaticity by a factor of 10 is expected from the nominal b_5 correction. This is considered sufficient for beam dynamics.

At top energy b_5 is expected to be close to zero in the main dipoles. Therefore, when the optics is squeezed, the dominant source of third chromaticity comes from the inner triplet quadrupoles Its value can reach 6 10^6 [13, Tab.4]. Its correction is not required at 7 TeV due to the small beam momentum spread.

4.6 AMPLITUDE DETUNING Q(J) AND CHROMO-GEOMETRIC DETUNING Q(J,δ)

In LHC, the beam tune spread is dominated at injection by the field imperfections of the main dipoles and at collision by the beam-beam effect and/or the Landau octupole scheme.

At injection, the expected main contributors, in order of importance, are $\langle b_4 \rangle$=0.2 units (before correction) and second-order terms in upright and skew sextupoles (lattice and random imperfections)[11]. The maximum anticipated detuning at 6σ is about 6 10^{-3} [11, Tab. 22 and Tab. 10] and drops to 2 10^{-3} after correction by the b_4 spool-pieces. A chromo-geometric detuning due to systematic b_5=1.1 units is as large as 9.4 10^{-3} at 6σ for δ=0.001 before b_5 correction. After correction with the b_5 spool-pieces, the residual is lower than 2 10^{-3} [11, Tab. 23].

At the end of the ramp, the amplitude detuning will be dominated by the Landau octupoles designed to produced an amplitude detuning $\Delta Q(6\sigma_{peak})$=2.2 10^{-3} [12] for particles with 6σ peak betatron amplitudes. After squeeze, the contribution of the triplets is negligible while the beam-beam interactions cause a tune spread as large as about 0.01 for nominal and 0.015 for ultimate proton parameters[14].

5. EXPECTED TOLERANCES ON THE OBSERVABLES / PARAMETERS

The analysis of the expected tolerances of the beam dynamics to variations in the beam parameters is done to specify the corresponding accuracy of the instruments.

5.1 TUNE AND TUNE SPREAD

Tracking studies at injection (LHV v6.0, [15]) show that the LHC working point is located almost at the centre of a stability island with a width corresponding to $\Delta Q=\pm 0.010$. The tolerance on the tunes can be deduced from this observation, after subtracting tune spreads and modulations [11, section 2.3.2]: $2\ 10^{-3}$ for the amplitude detuning, $2\ 10^{-3}$ for the chromo-geometric detuning $2\ 10^{-3}$ for the linear part of the chromatic tune modulation and $1\ 10^{-3}$ for the non-linear part. This leaves a tolerance $\Delta Q=\pm\ 3\ 10^{-3}$ for the adjustment of the central betatron tunes at injection.

In collision, the machine operates closer to the diagonal with a tune split of Q_y-Q_x=0.01, which corresponds roughly to the tune spread induced by the beam-beam effects. A safe operation of the LHC in collision requests a control of the betatron tunes with an accuracy better than $\Delta Q=0.001$, i.e. better than 10% of the tune separation.

Several mechanisms may induce a tune spread amongst the bunches:

- The electron cloud produces a tune shift which depends on the bunch position in a batch. A tune shift of the order 0.005-0.01 along a train has been observed at KEKB and in the SPS [16] and should be expected during the beam scrubbing.
- The Pacman effect induces a beam-beam linear tune shift which depends on the beam position. Its value is 0.001 for the nominal alternate crossing and might reach 0.003 if other crossing schemes remain possible [17].

5.2 COUPLING

In the presence of coupling, the minimum possible tune separation is given by the difference coupling coefficient c_-. At injection, the tolerance is $|c_-|<0.01$ [18]. In collision, from Sp$\bar{p}$S ISR experience, it shall be $|c_-|\leq 0.001$. The coupling is in general more detrimental to the beam diagnostics and feedback systems than to the beam dynamics. As a general rule, we wish to keep at less than 10% of the tune split.

5.3 LINEAR CHROMATICITY

The tolerance on chromaticity sharply depends on the beam current, the machine impedance and the assumptions on Landau damping. In the frame work of the 1997 assumptions [19], the tolerances were estimated as follows at injection:

- Single bunch, up to 10^{10} p: no constraint (Q'>-150)
- Nominal beam structure, 10% of nominal current: Q'>-15
- Nominal beam: Q'>0 and in practice ΔQ'=±1 for Q'=2.

Another limitation arises at injection from the sensitivity of the dynamic aperture to the linear chromaticity [20]. A loss equal to the safety margin of 20% is reached for +/-10 units.

In collision, since the transverse instability thresholds scale with $1/\gamma$, the constraint on Q' only comes from the minimisation of the tune ripple $\Delta Q=Q'\ \delta$ seen by the particle located at the edge of the RF bucket, i.e. with $\delta=0.36\ 10^{-3}$. Requesting the ripple amplitude to be less than 10% of the beam-beam induced tune spread, one gets a tolerance of ΔQ'=±3 units for the tolerance on Q' only when the beams are colliding head-on.

5.4 HIGHER-ORDER CHROMATICITY

After compensation at injection (i.e. by MCO spool-pieces for b_4 and the skew sextupole correctors MSS for a_3) and in collision (i.e. with the 4 lattice sextupole families), the second-order chromaticity should not exceed Q''=1000 and Q''=2000 units at injection and in collision, respectively [11, Tab. 6].

To preserve the DA at injection, b_5 must be known and corrected within 0.1 units which translates into a tolerance on Q''' is 0.5 10^6 [11, Tab. 6]. At top energy, the anticipated Q''' of 6 10^6 can be considered below significance.

5.5 AMPLITUDE DETUNING Q(J) AND CHROMO-GEOMETRIC DETUNING Q(J,δ)

The detunings at $6\sigma_\beta$ and maximum energy deviation are deemed to be insignificant for beam dynamics below 0.002 (see section 5.1 and 4.6 and further in section 11.5).

6. EXPECTED DYNAMIC EFFECTS

6.1 INJECTION PLATEAU

During injection at constant current excitation, the field imperfections of the main dipoles exhibit a drift 10 to 100 times slower than the changes observed during snap-back.

6.2 START OF THE RAMP AND SNAP-BACK

As soon as the main field changes, a rapid ``snap-back'' takes place in the super-conducting material whose magnitude roughly ranges from one fifth to one third of the magnetisation induced errors depending on the time duration at flat top and on the injection plateau (see eg. [21]). Its time constant is of the order of one minute thanks to the adiabatic start of the ramp. It cannot be significantly increased. The snap-back can be modelled to an estimated accuracy of 10 to 20% [22]. We assume in the following 1000 seconds and 30 minutes for the durations of the injection plateau and flat top and increase all values by 40% in the summary Table 3 to cover all cases [22].

- Tune drift: it arises from the slight change observed on the average b_2 (0.01 units measured on the first 70 magnets), from feed-down effects due the changing excitation $_{in}$ the b_3 spools (Δb_3 ~1.8 units => Δb_2 ~0.06 units for horizontal systematic misalignments of the MCS's by $\pm$ 0.3 mm) and from the change of b_1 (1.3 units measured so far) through the natural chromaticity Q'_{nat} . The total rate of variation of the tune is 1 10^{-3}/s. The random component of the b_1 and b_3 decay amounts to 1.1 and 0.5 units r.m.s., respectively. Therefore 40% of the b_1 decay and 80% of the feed-down effects could be anticipated using the 8 reference magnets, reducing the tune variation rate to ΔQ=0.4 10^{-3}/s.
- Coupling drift: the change observed on the average a_2 of the first 70 magnets is around 0.1 unit. Adding as previously 0.06 units for the dynamic skew quadrupole feed-down induced by the b_3 spools, this corresponds to variation rates $\Delta|c_-|\leq 0.8$ 10^{-3}/s for the difference coupling coefficient. The variation of the a_2 decay observed from magnet to magnet (0.3 units r.m.s.) is larger than the dynamic change. Hence only about 80% of the component coming from the feed-down effects can be fed forward. The variation rate is reduced to $\Delta|c_-|\leq 0.6$ 10^{-3}/s.
- Chromaticity drift: if not anticipated by the b3 spool-pieces, the snap-back of b_3 (Δb_3 ~1.8 units) induces a maximum rate of change of the chromaticity by 2.7 unit/s. Using the 8 reference magnets, this rate might be reduced to $\Delta Q'$=0.5 unit/s.

In addition to the super-conducting snap-back, discrepancies between the time constants of the various magnetic circuits may cause large excursions of the tunes, chromaticities…Estimates are presently not available. We presently assume that this effect is weaker than the snap back. It should be underlined that they cannot be decreased by a further reduction of the ramp rate which would deeply modify the snap-back effect [22].

6.3 RAMP

The ramp induced errors seen by the beam scale like $1/B \times dB/dt$. The magnetic measurements made so far show a negligible effect. The contribution of the magnetization decreases like $1/B^{1.5.}$ and gives as well a negligible effect. At the end of the ramp, the rate of change of the tunes is estimated to .0015/s. The dynamic effects during most of the ramp will thus be only slightly worse than during the injection plateau and much less than during the snap-back or squeeze.

6.4 SQUEEZE

During the nominal squeeze, the chromaticity changes by 60 units. The tunes and coupling may change as well due to imperfections (e.g. a non-vanishing closed orbit in the lattice sextupoles). Estimates of these imperfections are presently not available. One should expect small changes of parameters as compared to snap-back. Assuming that the squeeze will take place over a period of one minute and that the compensation of Q' by the lattice sextupoles will be done with an accuracy not better than ± 10%, the residual chromaticity variation rate should not exceed ΔQ'=0.1/s.

Table 3: Maximum variation rates of the observables on a typical time scale of 30 s

Observable	Worst case	anticipated
Q	$1.4\ 10^{-3}$ /s	$0.56\ 10^{-3}$ /s
Q’	~~3.8~~ 2.7/s	~~0.7~~ 0.5/s
coupling	$1.1\ 10^{-3}$ /s	$0.85\ 10^{-3}$ /s

7. CLEARANCE AVAILABLE FOR COHERENT OSCILLATIONS

In LHC, the maximum amplitude of the beam coherent oscillations must be limited to prevent a significant increase of proton losses onto the cold aperture. The threshold depends on the total current stored in the machine, on the energy and on the time scale for the beam oscillation. In addition, the dump surveillance interlocks will dump the beam if its transverse oscillations would reduce the extraction efficiency. Its threshold depends as well on total current and energy.

- **Pilot beam at injection**

The pilot bunch does not require collimation as its intensity is below the quench threshold. The 1D aperture of the machine being about 8.5σ, the oscillation amplitude could be as large as 6.5σ.

- **Injected batches**

At injection, the clearance foreseen for the injection oscillations in the collimation design is 1.5σ. This clearance is subsequently available for coherent oscillations at the injection energy on a similar time scale of 50 turns.

- **Nominal beams from injection to 7 TeV, pilot beam at 7 TeV**

A necessary condition is that the secondary collimator is never exposed to the primary beam. This is achieved for all phase shifts between primary and secondary if the maximum beam oscillation amplitude is 50% of *n2-n1*, i.e. 0.5σ. This limit is further enforced at the level of 0.6σ by the aperture restriction in the low-β quadrupole Q2 when the optics is squeezed (n1 ≈ 6.5σ).

This condition is however not sufficient. The beam oscillation causes the collimation inefficiency to grow, i.e. more particles are lost on the cold surfaces. In order to limit this increase to below 20%, the oscillation amplitude shall be limited to about 0.25σ [23, figure 2] at nominal current. At constant loss rate, the maximum amplitude may be increased inversely proportional to the beam current up to 0.5σ.

Depending on the collimation strategy during the ramp, the clearance for coherent oscillations can increase with energy along the ramp. It is advisable not to base the design on this peculiarity.

A summary of the allowed oscillation amplitudes is given in Table 6.

8. MAXIMUM BEAM MOMENTUM DEVIATIONS

Beam measurements may require changing the beam momentum. For DC momentum offsets, this should not exceed the machine momentum acceptance. For fast modulations, the bucket momentum acceptance is the relevant limit.

8.1 MACHINE MOMENTUM ACCEPTANCE

Under nominal conditions at injection energy, the machine momentum aperture is restricted to $\delta=\pm\ 1.5\ 10^{-3}$ by the momentum collimation system [24]. With a half-height RF bucket of $\delta=\pm\ 1.\ 10^{-3}$, the clearance for a dc momentum offset is $\delta=\pm\ 0.5\ 10^{-3}$. This is insufficient to allow the measurement of the field integrals of several multipole harmonics as a_3, b_4 or b_5 [25].

The momentum acceptance of the machine may be increased at injection energy for a pilot beam by retracting the momentum collimators and the secondary betatron collimators. The total momentum aperture reaches then $\delta=\pm\ 3.5\ 10^{-3}$ [26], leaving an effective clearance for a dc momentum offset of $\delta=\pm\ 2.5\ 10^{-3}$.

At collision energy, the momentum aperture shall further be limited to maintain the efficiency of the betatron collimation system: the parasitic dispersion there, coupled with a change of dc momentum, shall not shift the orbit too much. At commissioning time with a pilot beam, it is sufficient to ensure that the secondary collimator does not become a primary, i.e. that the orbit is shifted by less than 0.5σ for *n1-n2=1*. For higher currents, the drift shall be kept less than 0.25σ (see 7). The local orbit feedback can however be assumed to work efficiently by then. The chromatic displacement is one of the consequences of a momentum offset. A small β–beating arises as well from $\beta'(\delta)/\beta=200$ [13], at the 10% level for $\delta=5\ 10^{-4}$. The chromatic orbit displacement where the dispersion is nominally large may cause other orbit shifts or mismatches due to feed-down. We thus take a safety factor of 2:

$$\Delta D_C\,\delta \le \sigma_C/4\text{, i.e. }\ \delta \le \frac{\sigma_F}{4}\frac{1}{k_D D_F}$$

The subscript *C* refers to collimators and *F* to the focusing arc quadrupoles. k_D is the tolerance on dispersion beating taken to be 27% [24]. The dc momentum offset shall thus not exceed about $\pm\ 1.4\ 10^{-4}$ at collision energy.

8.2 BUCKET MOMENTUM ACCEPTANCE

Fast RF phase modulation is foreseen to measure the linear chromaticity in the LHC [27]. Since the RF bucket is almost full at 450 GeV, the induced momentum oscillations shall not exceed about 1/10 of the bucket half-height, that is $\delta_{dc} = \pm 1\ 10^{-4}$ in order to avoid particle losses or longitudinal emittance growth at injection. The tolerance is kept unchanged in collision, but for other reasons, related to beam-beam effects and/or based on collimation requirements (see previous section).

9. COHERENCE TIME FOR TRANSVERSE SIGNALS

9.1 DECOHERENCE DUE TO THE TRANSVERSE DAMPER

The parameters of the transverse dampers are given in [28]. The maximum kick that the damper can provide is 2μrad per turn (extending over 2 μs minimum) at 450 GeV. The damper gain is defined by the requirement to limit the emittance blow-up at injection to 2.5%. Whenever the injection damper is further needed as a transverse feedback system, the baseline scenario is to keep the electronic gain constant. This means that the decoherence time is independent of the oscillation amplitude but varies with the energy. Between the injection and collision energies, the decoherence time increases approximately like γ. If ever required, the strength of the damper should allow the damping of 1.5σ injection oscillations within 12 turns. Assuming an exponential damping, the estimated e-folding times are given in Table 4.

Table 4: Estimated coherence times (turns)

	Energy (GeV)	
	450	7000
Damper	46 [LHCDR6, 5.5.1]	620
Q'= ± 50	8	
Q'= 2 & Q'' = 11'000	130	
Beam-beam		250 (170 turns for ultimate beam intensity)

9.2 DECOHERENCE DUE TO THE TUNE SPREAD

After a kick, the coherence of the beam motion disappears after a characteristic time that depends on the r.m.s. tune spread:

$$\tau \approx 1/\left[2\pi\,\Delta Q(1\sigma_{\mathrm{rms}}, 1\sigma_{\delta})\right].$$

In the following, we do not distinguish between periodic decoherence/re-coherence (chromaticity effect in an otherwise purely linear machine) and irreversible decoherence as this seems immaterial for the measurements. The tune spreads are taken or calculated from the parameters given in section 4 ,

Table 5 and Table 8.

Table 5: RMS beam momentum spreads [web]

	450 GeV	7 TeV
P nominal	$3.06*10^{-4}$	$1.11*10^{-4}$
P Commissioning & First years & Ultimate	$4.7*10^{-4}$	$1.13*10^{-4}$
Pb ions	$3.9*10^{-4}$	$1.10*10^{-4}$

The main contributors are the following:

- a badly corrected chromaticity of +/- 50 units at injection corresponds to a "damping time'' of only 8 turns assuming a rms energy spread of σ_δ=4.7 10^{-4} r.m.s.
- After its correction, the main contribution to beam decoherence will be induced by a non-corrected Q'' of 11'000 units at 450 GeV, corresponding to a damping time of 130 turns.
- In collision, the dominant contribution to tune spread is given by beam-beam effects corresponding to a damping time of 250 turns for the nominal beam intensity (170 turns for ultimate beam intensity), and slightly more if the Landau octupoles are switched off.

All results are summarized in Table 4

10. SPECTRAL DISTORTIONS DUE TO COUPLINGS

In the LHC, the bunches are at least weakly coupled to the other bunches in the same beam thru the machine impedance and to bunches of the other beam thru the long-range interactions, even if the beams are `separated'. The transverse spectra will thus exhibit several peaks where the tune is hopefully dominant, but not necessarily. Figure shows a simulation of the spectrum of 2 colliding beams under nominal conditions [29]. The model assumes rigid bunches (no decoherence) and a vanishing machine impedance. One can already note several spectral frequencies of approximately similar amplitudes.

This calls for further studies to predict the transverse spectra, especially at injection, with separated beam, including the machine impedance and the decoherence. These studies should help designing the most robust tune finding algorithm.

Figure 1: Example of a simulated transverse spectrum for colliding beams

11. DESCRIPTION OF THE ANTICIPATED USES.

The default mode when measuring the betatron tunes, chromaticities, couplings… is to average over all bunches. There are however important exceptions where some of these parameters shall be measured bunch by bunch.

11.1 MEASUREMENT OF THE TUNES

11.1.1 MEASUREMENT OF THE INTEGER PART OF THE TUNES

This application is covered in the Functional Specification on the BPM system [30].

11.1.2 MEASUREMENT OF THE TUNES FOR COMMISSIONING

For commissioning the most robust and simple kick method is preferred. The transverse signal can be anticipated to be poor: the betatron coupling can be large (section 4.2) and the decoherence may occur within a small number of turns at injection energy (10 to 50, section 9). The conservation of the emittance is however not critical and a blow-up of up to 10% of the beam size per kick is acceptable. The induced coherent oscillation can thus reach $\sigma/2$. The tolerance on the tune of $\pm$ 3 10^{-3} (section 5.1) can probably be relaxed. We thus require a target global accuracy of $\pm$ 3 10^{-3} for an observation period of 50 turns, i.e. better than a FFT. The tunes should as well be calculated as soon as the beam circulates 3 turns following the method in [31].

11.1.3 MEASUREMENT OF THE TUNES FOR OPERATION

The machine is assumed to be well behaved, with a decoherence time reaching the maximum allowed by the damper and uncorrected non-linearities, i.e. between 50 and 150 turns at injection and up to 250 turns in collision. The maximum induced oscillation amplitude shall not exceed 0.5 σ at injection and 0.25 σ in collision to comply with the acceptance of the collimation system. The accuracy shall reach $\pm 2.5\ 10^{-4}$ to meet the tolerance on the tune in collision (section 5.1). During the snap-back and at the end of the ramp, it will be necessary to repeat the measurement at a maximum rate of 0.5 Hz (tolerance/max. drift = 0.003/0.0014, see sections 5.1 and 6). During injection, ramp and squeeze, the measurement rate can be reduced by at least a factor of 10. The maximum estimated total number of measurements for accumulation/ramp and squeeze is about 100 for an optimal continuous monitoring. The resulting emittance blow-up should ideally not exceed the LHC allowance of 7% overall. Should this turn out to be impossible, full monitoring would be used occasionally. The emittance increase should then be limited to some 20%. A larger blow-up could be handled by scraping, but this operation may be delicate in LHC.

11.1.4 MEASUREMENT OF THE TUNE SPREAD AMONGST BUNCHES

The tune shift along the bunch train is a sensitive signature of electron cloud activity (section 5.1). The range expected being 0.005 to 0.01, the resolution required on the bunch tunes is at least ±0.001.

If the bunches travel on slightly different trajectories (e.g. due to the PACMAC effect), the tunes will differ slightly. The expected tune range is of the order of 0.001 (section 5.1). This is at the limit of significance for beam dynamics. A resolution about 4 times better of ±0.00025 would be ideal but any value below ±0.001 is acceptable.

In both cases, the requirements on blow-up are relaxed if necessary.

11.1.5 THE TUNE FEEDBACK LOOP

The anticipated tune shifts due to the decay of the persistent currents and the snap-back are significant (see section 6); it is estimated that about 1/3 of the tune variation is not predictable and would require feedback. Without going into considerations of the stability of a feedback system, we simply require an over-sampling of the tune by a factor of 3 to allow a comfortably fast response time for the tune loop. This sets the maximum tune measurement rate to 0.5 Hz as in section 11.1.3. Under stable or quasi stable conditions (ramp), this rate can be reduced by a factor of up to 50. There should be no noticeable blow-up, i.e. less than a few percent. The sensitivity shall be 0.003, i.e. a global accuracy of a ±7 10-4.

These rates allow facing the tune variations due to anticipated effects. If it is technically possible (e.g. PLL), a continuous feedback (1 Hz or faster) might help in preserving beams in case of operation errors or e.g., transients on the mains.

11.2 MEASUREMENT OF THE COUPLING

11.2.1 CLOSEST TUNE APPROACH

This method based on the tune measurement versus quadrupole gradient (i.e. unperturbed tunes) is only of a limited interest (modulus of coupling only, slow measurement, delicate for hadron beams). It will certainly be used initially. This method requires being aware that the two eigenfrequencies will appear in each plane and should not confuse the processing algorithm of the beam spectrum. A measurement of the coupling to 0.01 is appropriate for commissioning (section 5.2). There is no additional requirement on the accuracy of the tune measurement.

11.2.2 COUPLING TRANSFER FUNCTION AND FEEDBACK

The preferred coupling measurement method is based on the transfer function [32], [33]. It does not perturb the machine like the closest tune approach and is liable to provide the two parameters of the coupling vector at a rate satisfying the requirements of a feedback. The beam excitor shall be able to excite the whole beam in the variants relevant to beam transfer function measurements: continuous band limited excitation, chirp excitation, single or dual frequency sinusoidal excitation with an adiabatic increase and decrease of the oscillation envelope (AC dipole mode). The detection of the oscillations can be made with the standard BPM's.

The feedback system will be most useful at injection and at the beginning of the ramp. From sections 5.2 and 6, the required maximum measurement frequency shall be about 0.25 Hz, including an over-sampling factor of 3 (0.0008/.01□3). In the rest of the cycle, it is likely that the correction frequency will be much reduced and will not require an automatic feedback. In order to minimize the consequence of the high measurement rate at the beginning of the ramp, use of high sensitivity resonant BPM's could be an advantage to minimize the beam blow-up. In this case, there should be two such BPM's separated by a drift space and a phase shift different from π (best is $\pi/2$).

The measurement precision shall reach $\pm$ 0.0025 (.01/4) during injection, ramp and squeeze and 10 times better in collision for accurate tuning.

11.3 MEASUREMENT OF THE CHROMATICITY

11.3.1 MEASUREMENT OF THE LINEAR CHROMATICITY

In the scenario of commissioning, the tune measurement to an accuracy of about $\pm 5\ 10^{-3}$ yields an accuracy in Q' of $\pm$ 5 for $\delta \approx 0.001$ for a beam circulating at least 50 turns. This is just within beam dynamics tolerances (section 5.3).

For nominal operation, the tolerance required on chromaticity is $\pm$ 1 (and $\pm$ units at 7TeV with head-on collisions). The momentum aperture is respectively $\pm 0.5\ 10^{-3}$ and $\pm 0.15\ 10^{-3}$ at injection and collision. The tune resolution for a tune-based measurement of the chromaticity shall thus be $\pm 0.25\ 10^{-3}$ at injection and collision. This is consistent with the requirement on nominal tune measurements….

11.3.2 THE CHROMATICITY FEEDBACK LOOP

During snap-back the chromaticity is liable to change drastically. The analysis of its drift rate and of the beam dynamics tolerance is done in sections 5.3 and 6. No special provision shall be anticipated for a pilot beam. For the 'first years' beam intensity, the chromaticity shall be measured at a frequency of 0.2 Hz (0.5/10□3) during the snap back, assuming that the Reference Magnet System predicts as anticipated 80% of the drifts. For the nominal beam intensity, the repetition rate should be increased to 1.5 Hz. However, recent advances in modelling the snap-back [34] should make it possible to reduce the chromaticity drift to 0.33/s (instead of 0.5/s). A measurement at about 1 Hz should be appropriate.

11.4 MEASUREMENT OF THE HIGHER-ORDER CHROMATIC DETUNINGS

The third order chromaticity provides the most direct measurement of the b_5 multipole and of the quality of its correction. This non-linear measurement can thus be assumed to be of importance. The second order chromaticity is anticipated to be of a lesser importance. In both cases, due to the very tight momentum aperture (section 8), the resolution required is large. The tune resolution required is given by:

$$\delta Q \approx \frac{1}{6}\left(\frac{5\,10^{5}}{3}\right)\delta^{3}\sqrt{5}$$

We take here the required resolution to be 1/3 of the sensitivity and assume a fit over 5 different momentum values instead of 10, given the high degree of the momentum dependence. To be able to measure b_5 within the momentum acceptance of the pilot beam at injection requires a resolution of the tune meter of the order of $\pm$ 1. 10^{-3}. For nominal beams however, the momentum window is reduced and the resolution shall reach better than 10^{-5}.

11.5 MEASUREMENT OF THE AMPLITUDE DETUNINGS, DYNAMIC APERTURE AND FREQUENCY MAPS

One of the design criteria of LHC is to keep the tune spread due to the anharmonicities to below 0.002 at 6σ. For this application the use of pilot pulses should be anticipated. Assuming a kicker rise time extending over a large number of bunches, a beam structure made of several pilot bunches spaced such as to sample the amplitude space every σ or σ/2 is optimal. Because of the risk of quench, the requested resolution is calculated for an oscillation amplitude of 4σ. The total tune shift to be measured is thus 0.001 with at least a quadratic dependence on the amplitude. The resolution of the tune measurement shall thus be of the order of a few 10^{-5}. For the measurement of the dynamic aperture, kicks of up to 6.5 σ are needed. At 7 TeV, it should be possible to kick at least two or three times the beam. This puts constraints on the kick duration. The horizontal and vertical kickers need be synchronized to produce skew kicks.

A powerful tool to visualize the non-linearity is the measurement of frequency maps [35]. This involves measuring the amplitude detunings for a large number of initial amplitudes in the real transverse space. The method has the same requirement as the dynamic aperture measurement. At 7 TeV, it would strongly benefit from short duration kicker pulses, e.g. for intermediate kick strengths.

11.6 MEASUREMENT OF LOCAL COUPLING & NON-LINEARITIES

This method is best tuned to correct locally the low-β insertions both for linear coupling and non-linearities. Given the complexity of the LHC low-β sections (correctors up to the dodecapole order, crossing angle and beam separation), it can be anticipated that this method shall be available early. The principle is to bump the beam in a source of multipole(s) and extract the multipole orders and strengths from the tune shifts [36]. Experience at Rhic shows that the method is best achieved with a continuous tune measurement at about 1 Hz and an accuracy of a few 10^{-6} for the tune shifts. The blow-up shall be limited to allow data collection over typically 30 minutes at least without significant beam loss. The beam intensity shall be limited to one pilot bunch if possible or one bunch with the minimum intensity or several pilot bunches, compatible with the accuracy demanded.

12. FUNCTIONAL REQUIREMENTS FOR THE MEASUREMENT SYSTEMS

12.1 OSCILLATION AMPLITUDES AND MOMENTUM OFFSETS

The maximum betatron oscillation amplitudes allowed (see section 7) are summarized in Table 6. The maximum momentum deviations that can be applied to the beam to measure off-momentum functions are given in Table 7.

Table 6: Clearance for beam oscillations

Beam Intensity	Operation phase	Amplitude limits			Maximum amplitude
		Cold bore	Collimation	Dump interlock	
#bunch □ charge		σ	σ	σ	σ
< 10^{11} total	injection	6.5	-	1.8	6.5*
1 □ 5 10^9	7 TeV before squeeze	6.5	0.5	7 (@7 TeV)	0.5, to 6.5 [MPWG]
1 □ 5 10^9	7 TeV after squeeze	0.6	0.5	7 (@7 TeV)	Not known
288 □ 1.15 10^{11}	injection	6.5	1.5	1.8	1.5
2808 □ 1.15 10^{11}	Filling and ramp	6.5	0.25	1.8 to 7	0.25
2808 □ 1.15 10^{11}	collision	0.6	0.25	7 (@7 TeV)	0.25

*: dump interlock disabled

Table 7: Maximum momentum deviations

energy	Scenario	Maximum dc momentum offset	Maximum ac momentum offset
injection	nominal	$\pm$ 0.5 10^{-3}	$\pm$ 0.1 10^{-3}
	Pilot, momentum collimators withdrawn	$\pm$ 2.5 10^{-3}	
collision	Pilot and nominal	$\pm$ 0.15 10^{-3}	

12.2 DYNAMIC RANGES

Table 8: Dynamic ranges covering all scenarios and maximum spread (or modulation) in any given scenario.

Parameter	Minimum		Nominal operation		Maximum		Spread or modulation
	450 GeV	7 TeV	450 GeV	7 TeV	450 GeV	7 TeV	

Q	.005		$.28 \rightarrow .32$		.495		-
Q′	-50		+2		50		0.02
Q″	-11000	-70000	0		11000	70000	$1.2\ 10^{-3}$
Q‴	$-5\ 10^{6}$	$-6\ 10^{6}$	~0	$0 \rightarrow 6\ 10^{6}$	$5\ 10^{6}$	$6\ 10^{6}$	$0.1\ 10^{-3}$
$\Delta Q(6\sigma_\beta)$	-.006	-.017	~0	$0.015 \rightarrow 0.017$	.006	.017	$0.9\ 10^{-3}$
$\Delta Q(6\sigma_\beta, 2\sigma_\delta)$	-.009	~0	~0		.009	~0	$0.2\ 10^{-3}$
|c|	-.1	.-0.05	0		.1	.05	-

12.3 PRECISION

For the parameters under consideration, we consider that the precision is only limited by the resolution. Systematic errors, when relevant, should be less than the resolution. In many cases, they are not relevant (tune shifts, chromaticity,…)

Table 9: Required precision versus parameters and scenarios

	Resolution		scenario
	on observable	on tunes	
Q	$\sim \pm\ 3.\ 10^{-3}$		Commissioning (50 turns)
	$\pm\ .7\ 10^{-3}$		Tune feedback
	$\pm .25\ 10^{-3}$		nominal
	$\leq \pm\ 1.\ 10^{-3}$		Bunch by bunch
	$< 10^{-5}$		Low-β non-linearities and studies
Q′	± 3	$\pm\ 3.\ 10^{-3}$	Commissioning (50 turns)
	± 0.33 to ± 1	$\pm .25\ 10^{-3}$	nominal
Q″	± 350	$\pm .15\ 10^{-3}$	Injection and ramp
	± 700	$\pm 3.0\ 10^{-5}$	collision
Q‴	$\pm\ 1.7\ 10^{5}$	$\pm .25\ 10^{-3}$	Pilot beam at injection
		$< 10^{-5}$	Nominal beam
$\Delta Q(6\sigma_\beta)$, $\Delta Q(6\sigma_\beta, 1\sigma_\delta)$	$\sim \pm 3.0\ 10^{-5}$		Pilot beam
|c|	$\pm 2.5\ 10^{-3}$		Injection and ramp, feedback
	$\pm .25\ 10^{-3}$		collision

The resolutions are taken to be about ¼ of the beam dynamics tolerances on the parameters. When the tune variations are used to calculate detunings, we assume at least 10 measurement points resulting in an improvement of the precision by a factor of 3. We quote here the tightest requirements.

12.4 REPETITION INTERVALS

The tunes, chromaticities and coupling are anticipated to require repetitive measurements during critical phases to allow feedback loops. The calculation of the repetition period assumes the resolutions given in Table 9, i.e. small as compared to beam physics tolerances. The number of samples is increased by a factor of 3 to allow redundancy. The repetition intervals are given in Table 10.

Table 10: Measurement repetition intervals in seconds

	Q	Q'	|c|
Injection plateau	100	-	≥ 100
Snap-back	2	5 (first years) ≥ 1 (nominal)	4
ramp	20	-	≥ 20
squeeze		≥ 5	
studies	1		

12.5 SYNCHRONIZATION

There must be flexibility to synchronize the measurements with external events of the machine. The anticipated uses considered in 11 already give a set of such events:

- Tune specific excitation systems (kickers, shakers)
- Other kickers (aperture, injection)
- RF frequency scans for chromatic dependence,
- Closed orbit bumps

12.6 BUNCH SELECTIVITY

In most cases, the beam average of the tunes, chromaticities,… are appropriate. The identification of the e-cloud effect requires a bunch-by-bunch measurement of the tunes. When the machine performance reaches the nominal level, a bunch by bunch measurement of the tunes and possibly of chromaticity is necessary.

12.7 DATA TO BE MADE AVAILABLE TO THE CONTROL ROOM

For all the rates foreseen in Table 10, the beam parameters shall be transferred in real time to the control room. A continuous display of the evolution of the beam tunes and possibly chromaticities shall be foreseen. In case of bunch by bunch measurements, the data shall rather be presented in a form of a histogram. It shall be possible to display the history of a few selected bunches.

12.8 POST MORTEM

All beam tune, chromaticity and coupling measurements shall be logged for post-mortem analysis.

13. FUNCTIONAL REQUIREMENTS FOR THE EXCITATION SYSTEMS

The tune measurement is so tightly linked to the beam excitation systems that it appears consistent to specify the latter in the same document. The requirements below stems from the analysis of the anticipated uses (section 11). We include as well the requirements from two additional uses:

- o the dynamic aperture measurement [37], which relies on the same equipment as the measurement of the amplitude detunings.
- o The beam-beam transfer function [38].

13.1 EXCITATION MODES

13.1.1 SMALL OSCILLATION AMPLITUDES (< 1σ)

- **Tune Kicker:** The traditional kick method remains of relevance due to its simplicity and robustness and will be required at commissioning.
- **Tune Shaker:** The continuous excitation mode is preferred for the measurement of the low-amplitude beam parameters. It opens the possibility of a continuous monitoring and of feedback loops. This makes studies as well much more efficient. It may either be
  - o Single frequency excitation
  - o Single frequency locked on the tune(PLL mode)
  - o Single or dual frequency with adiabatic rise anf fall-off (AC dipole mode),
  - o band-limited excitation,
  - o repetitive chirp excitation,

13.1.2 LARGE OSCILLATION AMPLITUDES

- **Aperture Kicker:** powerful kickers are needed to produce large amplitude oscillations up to 7 TeV (amplitude detuning, dynamic aperture).
- **AC dipole:** If technically feasible, this option is best suited to the LHC. It would allow obtaining large amplitudes with minimal risk of quenching magnets and repetitive measurements at 7 TeV.

13.2 EXCITATION STRENGTH

The strength of the kickers/shakers shall allow reaching the maximum amplitudes allowed in Table 6:

- Tune kickers: 1.5 σ at 450 GeV and 0.5 σ at 7 TeV
- Aperture kickers: 6.5 σ at up to 7 TeV
- o Shakers: lowest amplitude compatible with the demanded accuracy.

13.3 REPETITION RATE

The Tune kickers and the Tune shakers in chirp mode shall comply with the requirements specified in Table 10. There is no time constraint for the aperture kickers.

13.4 KICK SYNCHRONIZATION

The excitation in the two planes shall be synchronized at the bunch level to allow skewed kicks or continuous excitations.

13.5 SELECTIVE BUNCH EXCITATION

There are several distinct advantages to exciting single bunches or small trains of bunches:

- If the emittance growth due to tune or chromaticity measurements would limit the machine performance or produce background issues by populating distribution tails, it would be advantageous to `use up' one or a few bunches at once. The number of bunches is such that one kick per bunch would more than satisfy the requirements for an accurate machine control.
- Due to the beam collision schedule and the resulting Pacman and super-Pacman effects (at nominal luminosity), it may be advantageous to measure the tune on a subset of the bunches. Typically the 15 first and last bunches in a batch would be excluded. Such patterns could as well arise from electron cloud effects or perhaps from wakes.
- The beam-beam transfer function [lumispec] may be polluted if several bunches are kicked. This method allows a relative measurement of the luminosity insensitive to background issues.

The potential is sufficient to request at least a detailed study of a 40 MHz shaker to the smallest amplitude compatible with meeting the precision targets given in Table 9. Depending on cost and ressources, this device could be installed from the beginning or staged with a construction/installation delay not exceeding one year.

14. DESIGN CONSTRAINTS

14.1 ACTIVE DAMPERS

Transverse dampers will be used to damp injection oscillations and, most likely, throughout the run to eliminate transverse instabilities. The interference between the damper action and the excitors should be considered.

14.2 GEOMETRICAL ACCEPTANCE

The geometrical acceptance of the kickers, shakers and BPM's shall respect the LHC aperture standards. They have to be checked with the Working Group on Alignment (WGA, J.B. Jeanneret).

14.3 COUPLING IMPEDANCE

The coupling impedance of the kickers, shakers and BPM's shall respect the LHC impedance requirements standards. They have to be checked with the Impedance Working Group (F. Ruggiero).

14.4 INB CONSTRAINTS

The LHC has been classified as an "Installation Nucleaire de Base" by the French Authorities. CERN is therefore obliged to conform to their relevant regulations, guidelines and procedures. Within this context CERN has to establish traceability & waste management procedures and maintain a radiological and zoning system. In order to meet these requirements, information such as: material content, location history, sub-assemblies, etc…, shall be supplied by the Contractor and will be maintained in a CERN database. CERN has created a set of procedures and conventions as part of the Quality Assurance System for LHC, which will also be used to facilitate these INB requirements. The relevant quality documents are listed below and shall be applied by the Contractor during the production, testing and assembly of components: "The Equipment Naming Convention", "The LHC Part Identification", "The Manufacturing and Test Folder".

15. RELIABILITY, AVAILABILITY AND MAINTAINABILITY

16. SAFETY AND REGULATORY REQUIREMENTS

The longitudinal profile monitor must meet the safety guidelines put forward by the CERN Technical Inspection and Safety Commission (TIS). TIS have issued safety documents in compliance with LHC-PM-QA-100 rev1.1, and the guidelines in these documents will be incorporated into the monitor design.

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